

Hipparcos preliminary astrometric masses for the two close-in companions to HD 131664 and HD 43848

A brown dwarf and a low mass star

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ABSTRACT

Context. Several mechanisms for forming brown dwarfs have been proposed, which are today believed not to be mutually exclusive. Among the fundamental characteristics of brown dwarfs which are intrinsically tied to their origin, multiplicity is of particular relevance. Any successful determination of the actual mass for such objects in systems is thus worthwhile as it allows one to improve on the characterization of the multiplicity properties (e.g. frequency, separation, mass-ratio distribution) of sub-stellar companions.

Aims. We attempt to improve on the characterization of the properties (orbital elements, masses) of two Doppler-detected sub-stellar companions to the nearby G dwarfs HD 131664 and HD 43848.

Methods. We carry out orbital fits to the Hipparcos Intermediate Astrometric Data (IAD) for the two stars, taking advantage of the knowledge of the spectroscopic orbits, and solving for the two orbital elements that can be determined in principle solely by astrometry, the inclination angle i and the longitude of the ascending node Ω . A number of checks are carried out in order to assess the reliability of the orbital solutions thus obtained.

Results. The best-fit solution for HD 131664 yields $i = 55 \pm 33$ deg and $\Omega = 22 \pm 28$ deg. The resulting inferred true companion mass is then $M_c = 23^{+26}_{-5} M_J$. For HD 43848, we find $i = 12 \pm 7$ deg and $\Omega = 288 \pm 22$ deg, and a corresponding $M_c = 120^{+167}_{-43} M_J$. Based on the statistical evidence from an F -test, the study of the joint confidence intervals of variation of i and Ω , and the comparison of the derived orbital semi-major axes with a distribution of false astrometric orbits obtained for single stars observed by Hipparcos, the astrometric signal of the two companions to HD 131664 and HD 43848 is then considered detected in the Hipparcos IAD, with a level of statistical confidence not exceeding 95%.

Conclusions. We constrain the true mass of HD 131664b to that of a brown dwarf to within a somewhat statistically significant degree of confidence ($\sim 2 - \sigma$). For HD 43848b, a true mass in the brown dwarf regime is ruled out at the $1 - \sigma$ confidence level. The results are discussed in the context of the properties of the (few) close sub-stellar and massive planetary companions to nearby solar-type stars and their implications for proposed models of formation and structure of massive planets and brown dwarfs.

Key words. stars: individual: HD 131664, HD 43848 – planetary systems – astrometry – methods: data analysis – methods: numerical – methods: statistical – stars: low mass, brown dwarfs – stars: statistics

1. Introduction

Similarly to the detection of the first Jupiter-mass (M_J) planet orbiting a star other than the Sun (Mayor & Queloz 1995), the first unambiguous discovery of a brown dwarf¹ dates back ~ 14 years (e.g., Nakajima et al. 1995; Rebolo et al. 1995). Several mechanisms for forming brown dwarfs have been proposed: Turbulent fragmentation of molecular clouds, fragmentation of massive prestellar cores, protoplanetary disk fragmentation, dynamical ejection of protostellar embryos, and photoerosion of protostellar cores (for a review, see Whitworth et al. 2007). Such mechanisms are today believed not to be mutually exclusive, and they all likely operate in nature. To determine their relative contribution to the overall brown dwarf population is a major theoretical challenge. To date, agreement is still to be reached on fundamental issues such as the minimum mass for brown dwarfs,

and how brown dwarfs might be distinguished from planets. For example, if brown dwarfs are identified as objects that form like stars do, on dynamical timescales by gravitational instability, regardless of the formation locus (a molecular cloud or a marginally unstable protoplanetary disk) and if the minimum mass for core collapse is a few M_J (see Whitworth et al. 2007), then significant overlap between the mass range of brown dwarfs and planets would occur, and a simple mass cutoff (such as the one adopted here) may not apply. Given the significant number of open questions in this research field, it is thus essential for theory to accurately reproduce, and for observations to carefully determine, the ensemble properties of brown dwarfs, including the brown dwarf initial mass function, the young brown dwarfs kinematics, distribution, and disk frequency, and the binary statistics of brown dwarfs across a wide range of primary masses and orbital separations (for a review see Luhman et al. 2007 and Burgasser et al. 2007).

Among the fundamental characteristics of brown dwarfs which are intrinsically tied to their origin, multiplicity properties (e.g. frequency, separation, mass-ratio distribution) are of particular relevance, as together with the possibility of determin-

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¹ We operationally adopt the commonly used definition of brown dwarf as a deuterium-burning sub-stellar object with mass in the approximate range $15 - 80 M_J$

ing the actual internal composition and atmospheric features of individual objects, they constitute one of the few ways to observationally distinguish between planets and brown dwarfs in the possible overlap region in mass. For example, the frequency of close ($a < 5$ AU) stellar ($M_c > 0.08 M_\odot$) companions to nearby ($d < 50$ pc) solar-type stars is $13 \pm 3\%$ (Duquennoy & Mayor 1991), while in the same range of separations the frequency of giant planets ($M_c \lesssim 15 M_J$) is known today to be about 7% (Marcy et al. 2008). Brown dwarfs, on the other hand, appear conspicuously absent in the datasets collected by decade-long, high-precision radial-velocity surveys of thousands of bright normal stars, despite the fact that their large RV signals would have been easily spotted. Initial claims that the frequency of close brown dwarf companions seemed to be in fair agreement with a constant distribution of mass ratios (Mayor et al. 1992) where later dismissed by studies that showed, based on a combination of radial velocity measurements and Hipparcos astrometric observations, how most of these putative sub-stellar companions were in fact stars (Halbwachs et al. 2000). Indeed, among close companions, brown dwarfs appear outnumbered by stars and planets by factors of ~ 100 and ~ 50 , respectively, with typical frequency estimates of $\approx 0.1\%$ (Marcy & Butler 2000). Only about half a dozen close companions with minimum masses in the brown dwarf regime are known today around bright, nearby solar-type stars. It is conceivable that observational biases might somewhat contribute to a reduction of the discovery rate of brown dwarfs with respect to planets (massive companions being assigned typically lower priorities than lower-mass planets in Doppler surveys hard-pressed for optimal use of the precious observing time at 10-m class telescopes). However, such biases do not seem capable of explaining two orders of magnitude of difference in the observed frequency of brown dwarf companions with respect to planets and stellar companions.

The dearth of close brown dwarf companions to solar-type stars, commonly referred to as the 'brown dwarf desert' (e.g., Campbell et al. 1988; Marcy & Butler 2000), is seen to extend at wider separations. Only recently Patel et al. (2007) have reported the first radial velocity detection of a handful of companions with $M_c \sin i$ firmly established in the brown dwarf mass range at orbital distances of ~ 4 to 18 AU. These first results do not allow yet to produce an actual number for the brown dwarf frequency in this separation range. At larger separations ($\sim 50 - 1000$ AU), near-IR direct imaging surveys have confirmed a deficit in sub-stellar companions relative to stellar companions, but not quite as extreme as that apparent at orbital radii within a few AUs. McCarthy & Zuckerman (2004) find $f_{\text{BD}} = 1 \pm 1\%$, roughly a factor of ten lower than the stellar companion frequency in the same separation range. More recently Metchev & Hillenbrand (2009) have derived $f_{\text{BD}} = 3.2^{+3.1}_{-2.7}\%$, a number formally compatible with that of McCarthy & Zuckerman (2004). In any case, the abundance of wide-separation brown dwarf companions is comparable to that of free-floating brown dwarfs relative to stars. The evidence for a not-so-dry desert at wide separations is usually interpreted as supporting the view that brown dwarfs form by core fragmentation just like stars. However, the finer details of the formation mechanism are not well understood, as mentioned above, and a more accurate characterization of the multiplicity of brown dwarfs is needed in order to shed light on the relative role of the various proposed scenarios.

The dynamical determination of the mass of a few close brown dwarfs companions to low-mass stars and of brown dwarf binaries has been obtained for eclipsing systems for which both spectra can be observed (e.g., Zapatero Osorio et al. 2004;

Stassun et al. 2006), and by a combination of aperture masking interferometry and astrometry (Ireland et al. 2008). As for the sample of companions to nearby dwarfs discovered by Doppler planet surveys with $M_c \sin i$ values in the range between high-mass planets and brown dwarfs, it is conceivable that some of them are in reality stars seen pole-on. Similarly to Halbwachs et al. (2000), several authors have attempted to combine the radial-velocity orbits with Hipparcos astrometry in order to determine the inclination and true mass of the companions (for a review see for example Sozzetti 2009). Recently, Reffert & Quirrenbach (2006) presented low-significance detections of the astrometric orbits of the two outer companions in the HD 38529 and HD 168443 planetary systems, inferring masses in the brown dwarf regime of $37 M_J$ and $34 M_J$ for HD 38529c and HD 168443c, respectively. High-precision astrometry with HST/FGS allowed Bean et al. (2007) to determine an actual mass of $0.14 M_\odot$ for the companion to HD 33636, originally published with $M_c \sin i = 9.3 M_J$. Any successful attempt to resolve the ambiguity in the actual companion mass for such objects is thus worthwhile as it allows one to improve on the characterization of the multiplicity of brown dwarfs. This in turn permits to better understand the global nature of the sub-stellar companions found at larger separations by direct imaging surveys.

In this paper we present a new attempt at combining the information from Doppler measurements with Hipparcos astrometry to better the constraints on the mass of two Doppler-detected low-mass companions to HD 131664 (Moutou et al. 2009) and HD 43848 (Minniti et al. 2009), with published minimum masses in the low-mass brown dwarf regime. A summary of the available data in the literature for the two systems is presented in § 2. We derive improved constraints on the actual companion masses in § 3. Finally, in § 4 we a) put the new results in the context of the properties of the (few) close sub-stellar and massive planetary companions to nearby solar-type stars, collected in a catalogue table for ease of consultation and reference in future works, and b) discuss some of the implications of the present-day observational evidence for formation and structural models of massive planets and brown dwarfs.

2. Doppler data and Hipparcos astrometry

2.1. HD 131664

Included in the Doppler search for southern extrasolar planets carried out with the HARPS (Pepe et al. 2003) spectrograph on the ESO 3.6-m telescope at La Silla Observatory, the bright G-type star HD 131664 (HIP 73408) was recently announced by Moutou et al. (2009) to be orbited by a companion with minimum mass of $M_c \sin i = 18 M_J$ on an eccentric orbit of period $P \approx 5.3$ yr (for convenience, see Table 1 for a summary of the properties of the primary and of the orbital parameters of detected companion). At the distance of HD 131664, the inferred orbital separation ranges between 35 mas and 100 mas (as pointed out by Moutou et al.), making it a potentially interesting target for future direct imaging observations. The viability of this investigation depends in particular on the true mass of the companion and the actual contrast ratio. In the former case, high-precision astrometry with Gaia in space and VLTI/PRIMA from the ground (e.g., Sozzetti 2009, and references therein) will allow to derive accurate values of the actual mass of the companion. However, it must be noted that the minimum astrometric signature induced on the primary is just under 1 mas, as opposed to a median single-measurement error $\sigma_{\text{HIP}} \approx 3$ mas.

Table 1. Stellar characteristics of HD 131664 and HD 43848 and spectroscopic orbital elements for the two Doppler-detected companions. Reported errors are from the discovery papers.

Star Name	Sp.T.	V (mag)	π_\star (mas)	d (pc)	M_\star (M_\odot)	P (d)	T_0 (JD-2400000)	e	ω (deg)	K (m s ⁻¹)	$M_c \sin i$ (M_J)	a_1 (AU)
HD 131664	G3V	8.13	18.04	55.43	1.10 ± 0.03	1951 ± 41	52060 ± 41	0.638 ± 0.02	149.7 ± 1.0	359.5 ± 22.3	18.15 ± 0.35	3.17
HD 43848	G2V	8.65	26.99	37.05	0.89	2371 ± 840	53227 ± 65	0.690 ± 0.12	229.0 ± 9.0	544 ± 200	25.0	3.40

Hipparcos observations of this star could then help place useful mass constraints on the companion mass. Indeed, the Double and Multiple Star Annex of the Hipparcos Catalogue reports a G flag, indicating that a 7-parameter solution (allowing for acceleration in the proper motion) was found to significantly improve the standard 5-parameter single-star fit. The reported acceleration solution for HD 131664 is based on 96 datapoints, two of which corresponding to observations retained only by the NDAC consortium.

2.2. HD 43848

Doppler measurements taken with the MIKE echelle spectrograph (Bernstein et al. 2003) on the 6.5-m Magellan II (Clay) telescope have revealed (Minniti et al. 2009) the nearby solar-type star HD 43848 (HIP 29804) to be orbited by a companion with $M_c \sin i = 25 M_J$ on a high-eccentricity orbit with $P \approx 6.5$ yr (for completeness, Table 1 also reports the summary of the properties of the primary and of the orbital parameters of detected companion). This system also appears to be of potential interest for future direct imaging observations, with a separation at apoastron of ≈ 0.2 arcsec. Its minimum astrometric signature, at the distance of HD 43848, is ≈ 2.5 mas, a value comparable to the typical precision of Hipparcos astrometry for this star (median error $\sigma_{\text{HIP}} \sim 3.3$ mas). An astrometric solution with acceleration terms for this star is also present in the Hipparcos Catalogue, based on a total of 76 measurements² (with one abscissa retained only by FAST, one only by NDAC, and one rejected by NDAC in the solution). For both HD 43848 and HD 131664 there appears to be indication of the presence of a long-period trend in the Hipparcos data, rendering worthwhile a further investigation of the available astrometry.

3. Combined radial velocity+astrometry solution

When searching for evidence of the presence of orbital signal in Hipparcos data of a given star due to a spectroscopically discovered low-mass companion, a typical procedure is applied in which information from radial velocities is assumed known, and one resorts to probe the region of the parameter space not covered by spectroscopy. Orbital fits to the Hipparcos IAD are then usually performed (Mazeh et al. 1999; Halbwachs et al. 2000; Han et al. 2001; Zucker & Mazeh 2000; Reffert & Quirrenbach 2006; Wittenmyer et al. 2009) by keeping fixed four orbital elements (P , e , T_0 , ω) to their spectroscopically determined values and by solving for inclination an-

gle i and position angle of the ascending node Ω , with the additional constraint that the astrometric semi-major axis satisfies the equality (Pourbaix & Jorissen 2000):

$$a \sin i = 9.19 \times 10^{-8} P K \sqrt{1 - e^2} \pi_\star \text{ mas}, \quad (1)$$

where P is in days, the semi-amplitude of the radial velocity curve K is in m s⁻¹, and the orbital parallax π_\star is in mas. The resulting fitting procedure has then a total of 7 adjustable parameters, i.e. the five astrometric parameters (two position offsets in right ascension and declination, two differential corrections to the proper motion in right ascension and declination, and the parallax) plus i and Ω .

The experience of various authors indicates that one must be careful in not asking Hipparcos data to tell more than they actually can. Pourbaix (2001), Pourbaix & Arenou (2001), and later Zucker & Mazeh (2001) have for example shown that the Hipparcos IAD, while useful to put upper limits on the size of the astrometric perturbations, must be interpreted with great caution when attempting to derive actual astrometric orbits for sub-stellar companions with semi-major axes close to or even below the typical single-measurement precision of the satellite. So while the astrometric orbit does not need to be actually detected in order to derive constraints on the values of i and M_c , when not outright refuted (e.g., Pourbaix & Arenou 2001), reported detections usually have relatively low levels of statistical confidence (e.g., Reffert & Quirrenbach 2006). Based on the above considerations, we have adopted a multi-step approach to the treatment of the Hipparcos IAD for HD 131664 and HD 43848 in an attempt to make a statistically solid case for any conclusions we derive.

As a first step in the process, we decorrelated and weighted all available Hipparcos along-scan measurements for the two stars, following the prescriptions of Pourbaix & Jorissen (2000) and van Leeuwen & Evans (1998). We then asked whether an orbital model could result in an improved description of the Hipparcos data, and used the Thiele-Innes representation of a photocentric orbit (Heintz 1978) to carry out a linear least squares fit over a large grid of periods bracketing the ones obtained from the radial velocity measurements, while keeping fixed e and T_0 to their spectroscopic values. We thus sought to minimize

$$\chi^2 = \left(\Delta v - \sum_{k=1}^9 \frac{\partial v}{\partial p_k} \Delta p_k \right)^t \Sigma^{-1} \left(\Delta v - \sum_{k=1}^9 \frac{\partial v}{\partial p_k} \Delta p_k \right), \quad (2)$$

where the superscript t indicates transposed, Δv is the vector of along-scan Hipparcos IAD residuals to a single-star, 5-parameter fit, $\partial v / \partial p_k$ is the vector of partial derivatives of the along-scan

² Note that Minniti et al. (2009) looked for, and failed to find, hints of higher dispersion in the Hipparcos measurements for HD 43848 with respect to those of stars of similar magnitude and distance.

Table 2. Orbital fits to the Hipparcos IAD for HD 131664 and HD 43848, assuming knowledge of P , e , T_0 , and ω from the spectroscopic orbit. Adjustable parameters were corrections to the five astrometric parameters, i , and Ω . The resulting estimated masses of the companions are also given, based on the fitted value of the inclination angle.

Star Name	$\Delta\alpha$ (mas)	$\Delta\delta$ (mas)	$\Delta\pi_*$ (mas)	$\Delta\mu_{\alpha*}$ (mas yr ⁻¹)	$\Delta\mu_\delta$ (mas yr ⁻¹)	i (deg)	Ω (deg)	M_c (M_J)	$\chi^2_v(5)$	$\chi^2_v(7)$	$P(F)$
HD 131664	-2.8 ± 0.6	-2.1 ± 0.7	0.5 ± 0.9	-5.1 ± 0.7	-4.1 ± 0.8	55 ± 33	22 ± 28	23^{+26}_{-5}	1.39	1.15	0.001
HD 43848	-4.9 ± 0.7	-9.8 ± 0.8	0.1 ± 0.9	-8.6 ± 0.3	0.3 ± 0.9	12 ± 7	288 ± 22	120^{+167}_{-43}	1.67	1.22	0.0002

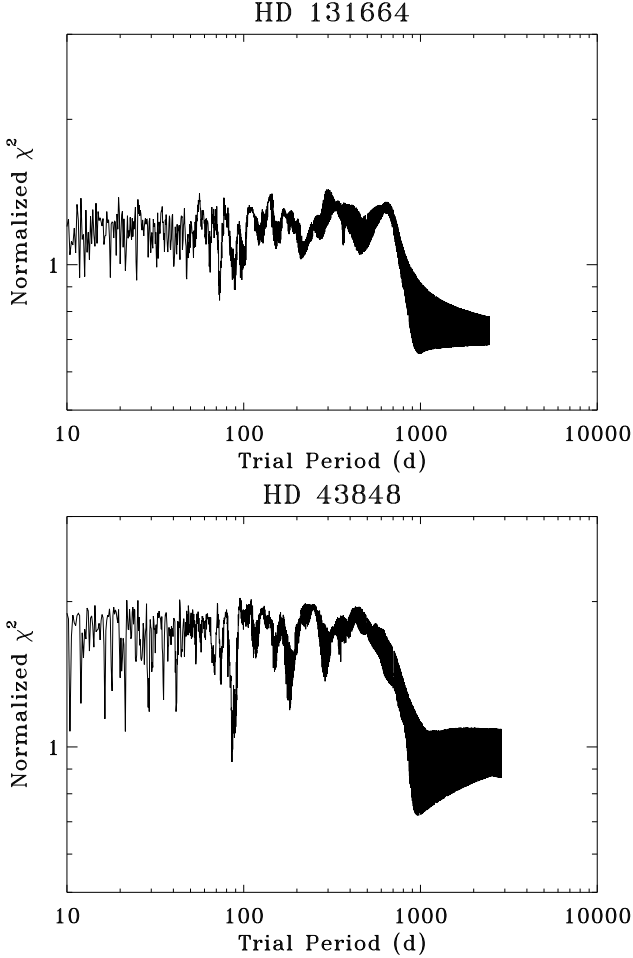


Fig. 1. Periodograms of HD 131664 (top) and HD 43848 (bottom) assuming e and T_0 from the known spectroscopic orbit.

coordinate with respect to the k -th fitted parameter, Δp_k the relative correction, and Σ^{-1} is the inverse of the covariance matrix of the solution. The fitted model is fully linear in 9 parameters, i.e. the five astrometric ones and the four Thiele-Innes constants A , B , F , and G . The results of this period search are shown for both stars in Figure 1. The presence of a long-period trend in the data appears clear for both HD 131664 and HD 43848, in clear accord with the choice of an acceleration solution for both objects at the time of publication of the Hipparcos catalogue. The orbital period is well-known from spectroscopy in the case of HD 131664 (Moutou et al. (2009) report uncertainties on the order of $\sim 2\%$), but less so for HD 43848 (uncertainties reported by Minniti et al. (2009) are on the order of $\sim 17\%$). Despite this,

and the fact that Hipparcos only covered a fraction of the orbit path of both objects, it is nonetheless worthwhile to investigate whether a full-fledged orbital solution can be extracted from the Hipparcos data, which robustly passes statistical screening. Following a procedure similar to that adopted by others and outlined above, we then fitted the Hipparcos IAD for the two objects keeping P , e , and T_0 fixed at their spectroscopic values, while adjusting the five correction terms to the astrometric parameters³, i and Ω (with the additional constraint of Eq. 1). We adopted a dense two-dimensional grid of starting values for both i and Ω , in order to solve a local non-linear minimization problem in which we used a model function expressed in terms of the Campbell orbital elements. In order to assess the impact of the more or less precise knowledge of the spectroscopic orbit, the procedure was re-run 100 times, each with a different set of (fixed) spectroscopic orbital elements drawn from gaussian distributions with mean and standard deviation the best-fit value and its formal error, respectively.

The results of the orbital fit to the Hipparcos IAD of both HD 131664 and HD 43848 are summarized in Table 2. The reported uncertainties on i and Ω , as well as the derived mass values for the companions, take into account the $1-\sigma$ formal errors on the parameters of the spectroscopic orbits. The inferred true masses for HD 131664b and HD 43848b are $23^{+26}_{-5} M_J$ and $120^{+167}_{-43} M_J$, respectively. Taken at face value, these numbers would imply that the companion to HD 131664 has a mass in the brown dwarf regime at the $2-\sigma$ confidence level, while the unseen object around HD 43848 is likely a low-mass M dwarf (at the $1-\sigma$ confidence level). An attempt at using the FAST and NDAC data separately for both stars resulted in solutions formally compatible with the ones reported here, albeit with larger uncertainties and looser constraints on the derived mass estimates.

In order to assess the statistical soundness of the derived astrometric orbits, several checks can be performed. First, based on an F-test of the null hypothesis that there is no companion, we find that the addition of two parameters to the model describing the Hipparcos IAD significantly improves the fit in both cases: $P(F) = 0.0002$ and $P(F) = 0.001$ for HD 131664 and HD 43848, respectively. Second, similarly to Reffert & Quirrenbach (2006), we have further explored the reliability of the orbital solutions by inspecting the joint confidence regions (corresponding to iso- χ^2 contours) in the $i-\Omega$ plane, for a given statistical level of confidence. As shown in Figure 2, the 95% ($2-\sigma$) iso- χ^2 contours cover relatively narrow regions in the $i-\Omega$ plane, ruling out with confidence very small inclinations in the case of HD

³ We used in the fitting process both π_* and its transformed value $\pi'_* = \log \pi_*$, a trick utilized by Pourbaix & Jorissen (2000) to prevent parallaxes from becoming negative, and converting back to π_* at the end of the minimization procedure. No significant differences in the final results were found.

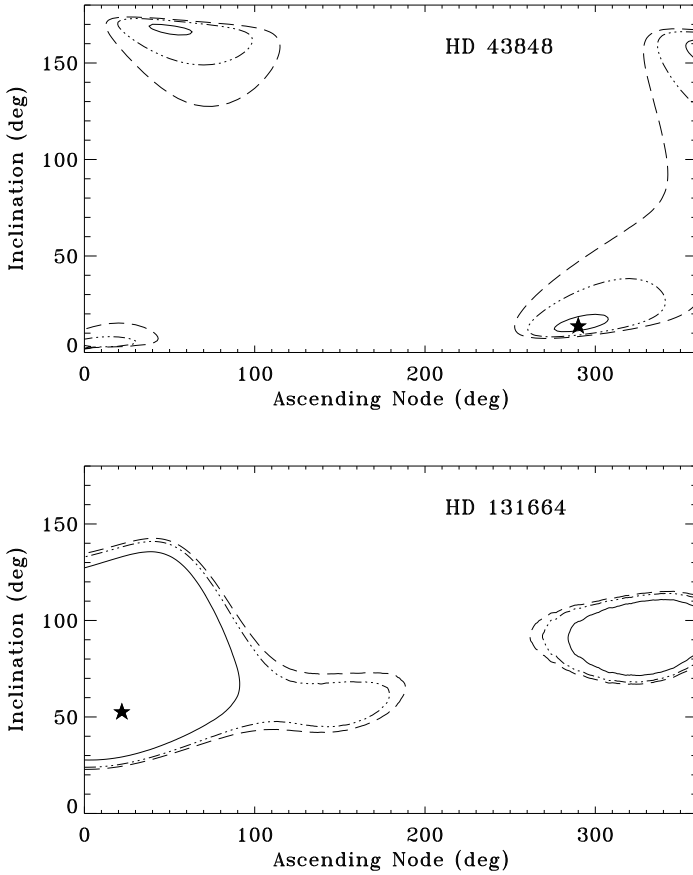


Fig. 2. Iso- χ^2 contours corresponding to confidence intervals in two dimensions containing 68.3% (solid line), 90% (dashed-dotted line), and 95% (dashed line) of the values of i and Ω as obtained in a 7-parameter fit to the Hipparcos IAD of HD 43848 (top) and HD 131664 (bottom), assuming P , e , T_0 , and ω from the known spectroscopic orbit. The best-fit (i, Ω) solutions for both stars are indicated with stars.

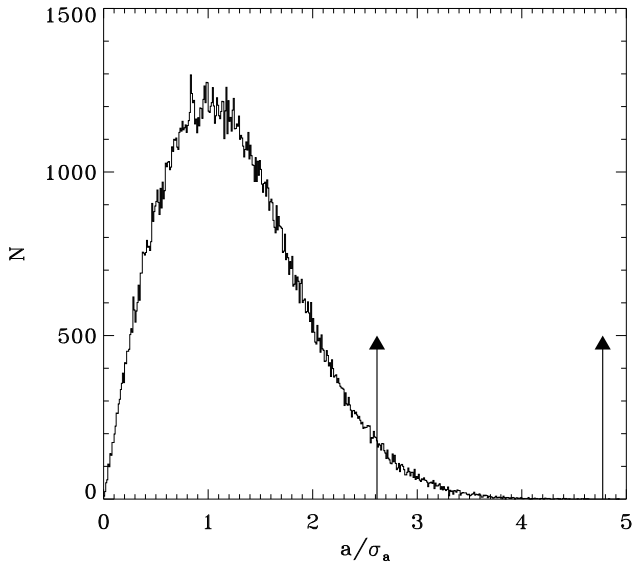


Fig. 3. Distribution of the ratio a/σ_a of false astrometric orbits for single stars observed by Hipparcos, approximated by a Rayleigh-Rice law following Halbwachs et al. (2000). The two arrows indicate the values of a/σ_a obtained for HD 43848 and HD 131664 based on a Monte Carlo bootstrap simulation.

131664, and close to edge-on configurations in the case of HD 43848. Ambiguities in the orbit orientation are clearly seen in both cases, highlighted by local minima in the χ^2 surface corresponding to configurations with the opposite sense of revolution. Nevertheless, one would conclude that Hipparcos astrometry has successfully detected orbital motion induced by the two massive companions to HD 131664 and HD 43848. We consider the 95% confidence level as the appropriate measure of the degree of statistical robustness with which these results can be regarded. Finally, we have applied a standard bootstrap method (Efron 1982), based on 1000 Monte Carlo resamples with replacement, to the available data for both stars in order to derive empirical error estimates on the derived orbital semi-major axes (constrained by Eq. 1 during the fits). Our procedure closely follows the one adopted by Zucker & Mazeh (2001), who first realized, due to the assigned correlation between pairs of Hipparcos measurements for which both FAST and NDAC data are available, the need to preserve the pairing of the measurements while drawing new random datasets, in order to make the bootstrap method applicable in the first place. The two resulting ratios a/σ_a have then been compared to the Rayleigh-Rice law distribution of *false* a/σ_a one can expect to obtain in the case of Hipparcos data of single stars (see (Halbwachs et al. 2000)). As shown in Figure 3, the nominal values of a/σ_a for HD 131664 and HD 43848 fall in the tail of the Rayleigh-Rice distribution: the probability that a/σ_a exceeds the observed one is found to be 0.03 and 2×10^{-5} for HD 43848 and HD 131664, respectively. This can be again interpreted as a detection of a significant Hipparcos astrometric orbit for both stars, at the 97% and 99.99% confidence level, respectively. For the purpose of this study, we adopt the more conservative abovementioned 95% confidence level to gauge the actual degree of statistical confidence with which the orbits of HD 43848b and HD13664b are considered detected.

4. Summary, discussion, and conclusions

We have inspected the Hipparcos IAD for two stars, HD 43848 and HD 131664, with Doppler-detected companions with minimum masses in the brown dwarf regime. We have presented a body of supporting evidence which appears to confirm the detection of orbital motion in the Hipparcos IAD of HD 43848 and HD 131664, at a somewhat significant (95%) level of statistical confidence. The inferred actual masses of HD 43848b and HD 131664b are found to be $M_c = 120^{+167}_{-43} M_J$ and $M_c = 23^{+26}_{-5} M_J$, respectively. The former thus appears to be a late M dwarf (at the $\sim 1 - \sigma$ confidence level), while the latter appears to be a brown dwarf (at the $\sim 2 - \sigma$ confidence level). Taken at face value, HD 131664b is nominally the lowest-mass brown dwarf confirmed with a combination of Hipparcos and precision Doppler measurements (the astrometric orbits of giant planets obtained with HST/FGS + RV data lie in a different ballpark). The larger uncertainties in the spectroscopic orbital elements of HD 43848, combined with the low value of i inferred from the orbital fit, translate in larger uncertainties in the mass estimate, leaving margin for this unseen object to also be a brown dwarf (as well as a higher-mass M dwarf).

Based on the mass-luminosity relations of Delfosse et al. (2000), HD 43848b, with its nominal mass of $120 M_J$, is expected to have magnitude differences of about 8.7, 5.7, 5.4, and 5.2 in the V, J, H, and K bands, respectively. With a projected separation of about 0.15 arcsec at apoastron it should be detectable with current AO instruments at 8m class telescopes. The magnitude difference between HD 131664b and its parent star depends critically on the age of the system.

Moutou et al. (2009) give an age of 2.4 ± 1.8 Gyr for HD 131664 based on isochrone fitting. Additional clues can be derived from stellar activity indicators. Moutou et al. (2009) measured $\log R'_{HK} = -4.82 \pm 0.07$. This corresponds to an age of 3.5 Gyr using the calibration by Mamajek & Hillenbrand (2008). We also searched for X-ray emission from the system. The ROSAT Faint Source Catalog (Voges et al. 2000) includes a source (1RXS J150003.3-733128) at 40 arcsec from HD 131664 (with a quoted positional error of 29 arcsec). The association is then doubtful. Assuming 1RXS J150003.3-733128 is the X-ray counterpart of HD 131664, we derived (using the flux calibration by Hünsch et al. (1999)) $\log L_X = 28.5$ and an age of 2.1 Gyr (using the calibration by Mamajek & Hillenbrand (2008)). Alternatively, a null detection would imply an older age. Stellar activity indicators then exclude the youngest stellar ages compatible with isochrone fitting. A more plausible lower limit to the stellar age is about 1.5 Gyr. HD 131664b, given our best-fit mass value and the age of 2.4 Gyr, is expected to have magnitude differences of about 15.0, 15.2, and 17.2 in J , H , and K bands respectively, based on the models of Baraffe et al. (2003). The corresponding effective temperature is about 700 K, at the cool end of the currently known T dwarfs. Considering the small projected separation (< 0.1 arcsec), such a contrast is not achievable with current instrumentation, and it would also be challenging for the next generation of direct imaging instruments.

Any successful attempt, such as the one presented here, at deriving true masses of the substellar companion candidates detected from radial velocity surveys is definitely worthwhile, as the results can be seen in the context of the observed paucity of close brown dwarf companions to solar-type stars in the solar neighborhood, the well-known brown dwarf desert, and in particular their binarity properties. For example, taken at face value the rather large eccentricity of HD 131664b ($e = 0.638$) supports the notion that massive planetary companions and brown dwarfs are preferably found on eccentric orbits (Ribas & Miralda-Escudé 2007). On the other hand, the high metallicity of the parent star ($[Fe/H] = +0.32$) does not follow the proposed trend of metallicity vs. mass for substellar companions (Ribas & Miralda-Escudé 2007). While not conclusive, these findings bring new/updated information that can certainly help to better our understanding of the formation mechanism of such objects.

4.1. Properties of massive planets and brown dwarf companions to solar-type stars

To put our discussion in a more general context, we summarize in Table 3 the main properties of the companions with projected masses between 10 and $80 M_J$, and semimajor axis smaller than ≈ 7 AU, orbiting main-sequence stars with masses between 0.7 to $1.5 M_\odot$. This selection matches the sample of most high-precision radial velocity surveys and avoids the additional complications of large variations in the stellar mass and evolutionary status (very small number statistics being one of the most relevant). The literature data collected here are meant to provide ease of consultation and reference for future works on the many outstanding issues we touch upon thereafter. In the Table, the determination of or constraints on the inclination and true companion mass derived from astrometry or transit photometry are included when available. For completeness and reference, we also include companions with substellar projected mass and astrometrically derived stellar mass. We have also included HD 33636, whose companion with $M_c \sin i$ just below the adopted threshold was shown to be a low mass star (Bean et al. 2007).

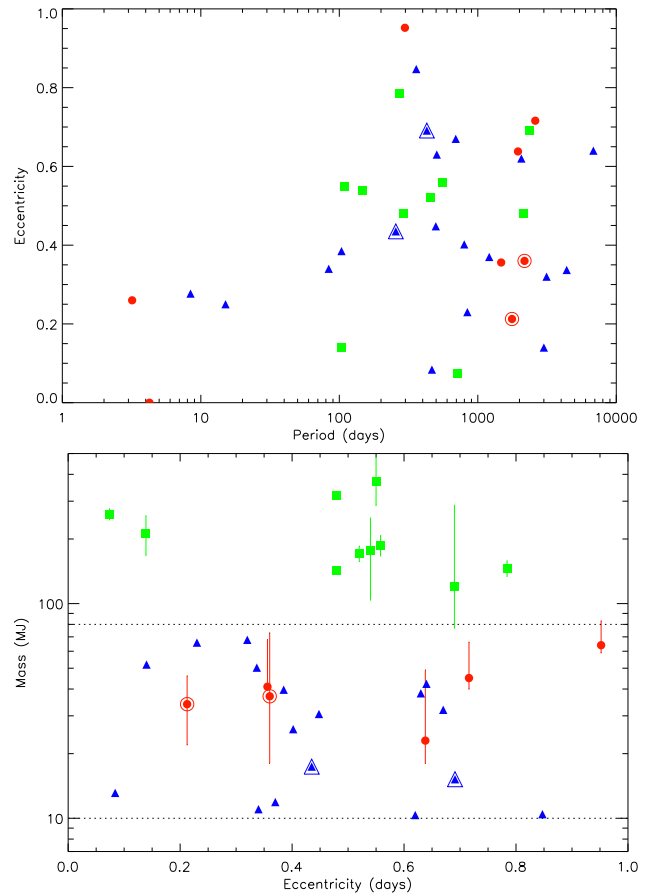


Fig. 4. Period vs eccentricity (top panel) and eccentricity vs companion mass (bottom panel). In the lower panel plot only objects with period longer than 20 days are shown). Red filled circles: companions with true estimated masses in the range 10–80 M_J . Blue triangles: companions with projected masses in the range 10–80 M_J . Green squares: companions with projected masses in the range $< 80 M_J$ but true stellar masses $> 80 M_J$. The three objects with larger symbols belong to the multiple systems HD 38529, HD 168443 and HD 202206.

Orbital elements and projected masses are from listed discovery papers, Butler et al. (2006) or Halbwachs et al. (2000). Stellar masses and metallicities are from Valenti & Fischer (2005), discovery papers or additional references. Further information, such as additional stellar or planetary companions, the sources for the metallicity values, and the specific treatment of some of the mass and error estimates, can be found in the notes.

As discussed in the Introduction, Halbwachs et al. (2000) have shown how a significant fraction of Doppler-detected candidate substellar companions were in fact low-mass stars viewed at low inclination. Nevertheless, a few candidates have masses firmly in the substellar regime, partially filling the brown dwarf desert. Interestingly, in two cases (HD 38529 and HD 168443) additional companions in the planetary mass regime were found.⁴ We note that such system configurations are more typical of planetary systems than of multiple stellar systems.

⁴ Two additional probable cases of a system with a brown dwarf and a planet in close orbits are those of HAT-P-13 (Bakos et al. 2009) and HD 202206 (Correia et al. 2005). In the first case, the planetary nature of the inner companion is confirmed by the occurrence of the transit. The true masses of the more massive companions are not available but there are perspectives for deriving them thanks to the strong dynamical

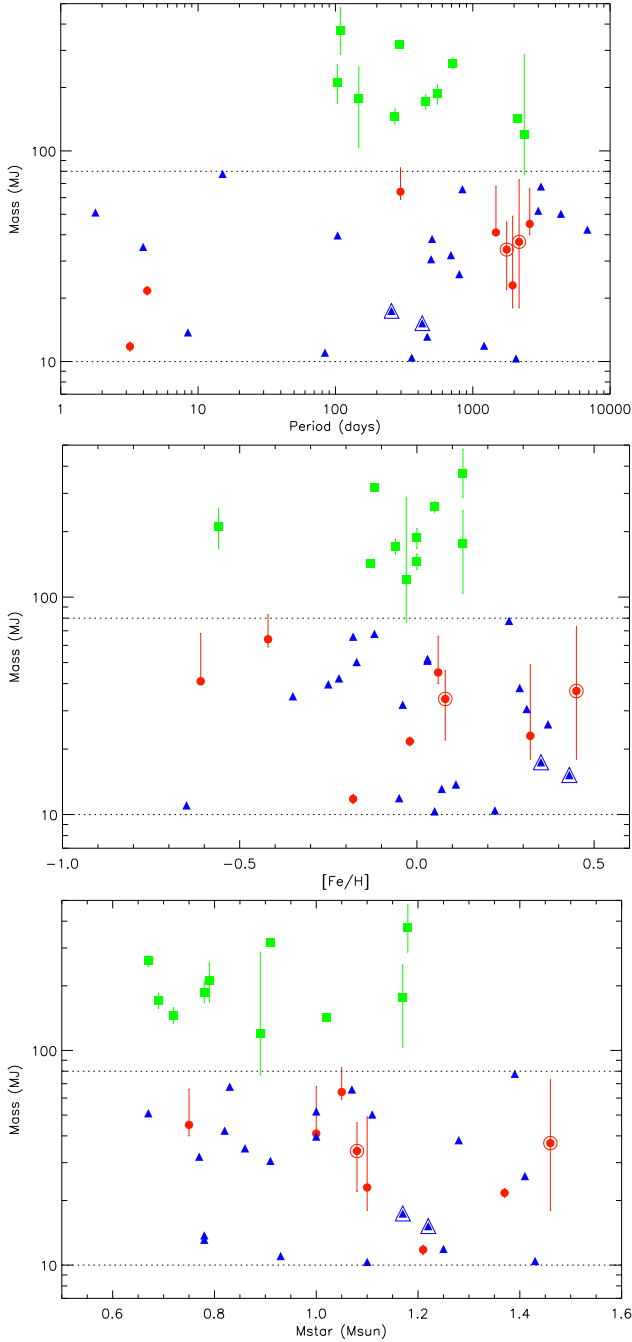


Fig. 5. Orbital period vs companion mass (top), metallicity vs companion mass (center), stellar mass vs companion mass (bottom). Symbols as in the previous Figure.

In Figure 4 and Figure 5 we show a set of correlation diagrams among the most relevant quantities of the systems collected in Table 3.

Ribas & Miralda-Escudé (2007) noted a possible trend in the eccentricity-mass distribution of giant planets, with more massive planets ($M_c \sin i > 4 M_J$) orbiting on average with larger eccentricities. The recent analysis by Wright et al. (2009), who used $1 M_J$ as the cut-off value, confirm this trend. The Ribas & Miralda-Escudé (2007) analysis also suggested that the metallicity of stars hosting massive planets and brown

interactions in the case of HD 202206 and the transit timing variations in the case of HAT-P-13.

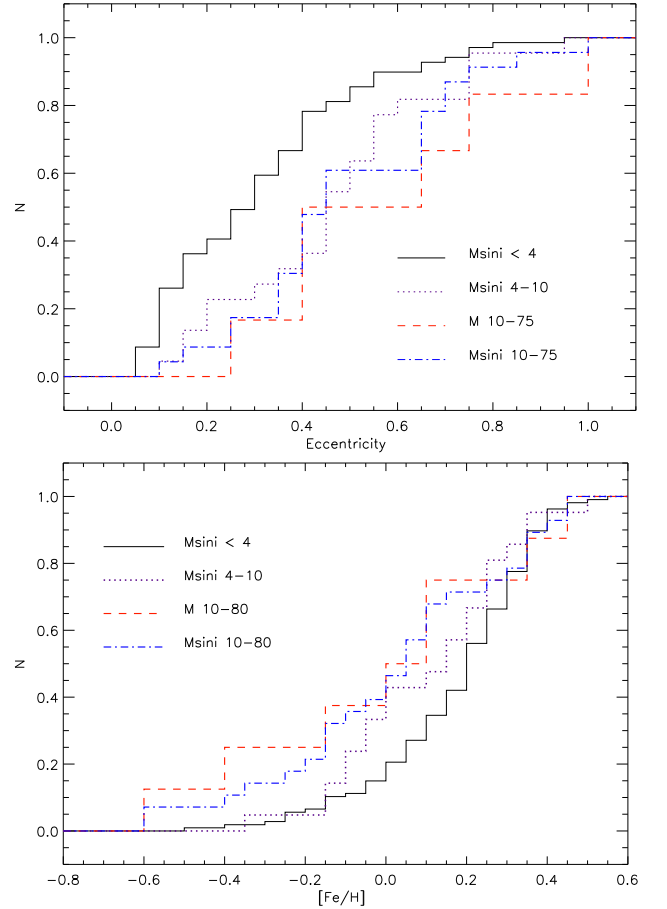


Fig. 6. Upper panel: cumulative distribution of the eccentricity of objects with period longer than 20 days orbiting main-sequence stars with mass between 0.7 and $1.5 M_\odot$. Continuous (black) line: planets with $M_c \sin i < 4 M_J$ (from Butler et al. (2006)). Dotted (purple) line: planets with $4 < M_c \sin i < 10 M_J$ (from Butler et al. (2006)). Dashed (red) line: objects with mass $10 < M_c < 80 M_J$ (this paper). Dashed-dot (blue) line: objects with $10 < M_c \sin i < 80 M_J$, but excluding objects with astrometric masses in the stellar regime (this paper). Lower panel: cumulative $[\text{Fe}/\text{H}]$ (with no period cut). Same symbols as in the upper panel.

dwarf candidates is compatible to that of the solar neighborhood ($[\text{Fe}/\text{H}] \approx -0.15$, e.g. Nordström et al. 2004), differing at the $3\text{-}\sigma$ level from the super-solar metallicity distribution of stars hosting lower mass planets ($[\text{Fe}/\text{H}] \approx +0.24$, e.g. Fischer & Valenti 2005). Hints of such a trend had already been seen in a more limited dataset by Rice et al. (2003). We revisit here this statistical analysis, considering all objects included in Table 3 as well as the sample of exoplanets with $M_c \sin i < 10 M_J$ reported in Butler et al. (2006). For this purpose, we have divided the full sample in three subsets according to minimum mass: $M_c \sin i < 4 M_J$, $4 < M_c \sin i < 10 M_J$, and $10 < M_c \sin i < 80 M_J$, plus a fourth subsample formed by those objects in Table 3 with estimated true masses in the range $10 < M_c < 80 M_J$. We have then performed on these subsets a Kolmogorov-Smirnov (K-S) test, to measure to what extent their e and $[\text{Fe}/\text{H}]$ distributions might differ, and a Wilcoxon Rank-Sum (R-S) test, to measure to what degree the mean e and $[\text{Fe}/\text{H}]$ might be considered different. The resulting values of the probabilities ($\text{Pr}(D)$ and $\text{Pr}(Z)$, respectively) of the null hypothesis for both tests on

Table 4. Results of the K-S and R-S tests on different subsets of systems: all planets from the Butler et al. (2006) catalog with $M_c \sin i < 4 M_J$ (1), companions with $4 < M_c \sin i < 10 M_J$ (2), companions with $10 < M_c \sin i < 80 M_J$ but excluding those with confirmed mass larger than $80 M_J$ (3), and companions with true masses in the range $10 < M_c < 80 M_J$ (4).

Sub-sample	D	$Pr(D)$	Z	$Pr(Z)$
Eccentricity Distribution				
1 vs 2	0.435	0.002	3.142	0.001
1 vs 4	0.50	0.08	2.18	0.01
1 vs 3+4	0.449	0.001	3.4535	0.0003
2 vs 4	0.32	0.64	0.73	0.23
2 vs 3+4	0.21	0.65	0.24	0.41
Metallicity Distribution				
1 vs 2	0.22	0.27	-0.67	0.25
1 vs 4	0.46	0.06	-1.57	0.06
1 vs 3+4	0.389	0.002	-2.745	0.007
2 vs 4	0.31	0.51	-1.11	0.13
2 vs 3+4	0.28	0.23	-1.36	0.09

the various subsamples are reported in Table 4, while Figure 6 shows a comparison between the resulting cumulative distributions of e and $[Fe/H]$ for the abovementioned subsets of systems.

From investigation of Table 4 and Figure 6, a few conclusions can be drawn. As for the e distribution, the results further corroborate the notion that eccentricities of not so massive planets are clearly less pronounced than those of more massive planets and brown dwarf companions⁵. On the other hand, massive planets appear to have an overall e distribution which is indistinguishable from that of brown dwarf candidates. Similarly, the $[Fe/H]$ distribution of the hosts appears significantly different for companions with $M_c \sin i < 4 M_J$ and for brown dwarf companions, while other trends are marginal, and in particular metallicities of massive planet hosts and of primaries with brown dwarf companions are statistically the same.⁶

4.2. Implications for formation and structural models of massive planets and brown dwarfs

The above evidence can be interpreted, keeping in mind the relatively small-number statistics regime we’re dealing with here, in the context of the proposed formation scenarios and internal structure models of high-mass planets and brown dwarfs, and as a function of the main properties of the stellar hosts (binarity, mass, metallicity).

⁵ The statistical analysis presented here does not take into account the eccentricity bias in Keplerian fits to Doppler data collected by radial-velocity planet search programs, which a) underestimates the abundance of low-amplitude, low-eccentricity planets, and b) makes low-amplitude, high-eccentricity planets hard to unveil (Shen & Turner 2008; O’Toole et al. 2009; Valenti et al. 2009)

⁶ It also appears that the brown dwarfs with the largest actual mass estimates seem to be found more frequently as close companions to stars belonging to the thick disk population of the Milky Way (see Table 3), but this can only be regarded as a tentative speculation, given the very limited statistics, large mass uncertainties, and heterogeneity of the datasets.

4.2.1. Formation and orbital evolution of massive planets and brown dwarfs

As already remarked in the Introduction, the lower mass limit for the formation of self-gravitating objects from fragmentation of molecular cloud cores is today thought to be on the order of a few M_J (e.g., Whitworth et al. 2007; Luhman et al. 2007). Ribas & Miralda-Escudé (2007) and, more recently, Font-Ribera et al. (2009) proposed direct cloud fragmentation, followed by inward migration by disk capture, as a formation mechanism for the high-mass tail of the planetary population. The detection of a significant number of free-floating objects down to $\sim 6 M_J$ and the observed continuity of the substellar mass function in young star forming regions (e.g., Caballero et al. 2007, and references therein; Zuckerman & Song 2009, and references therein) are indications that indeed a star-like formation process may form brown dwarfs as well as planetary mass objects⁷. Indeed, the process outlined by Font-Ribera et al. (2009) should be effective independently of the metallicity of the parent cloud, and is expected to produce an eccentricity distribution similar to that of binary systems. The results shown in Table 4 and in Figure 6 can be seen as supportive of this scenario. On the other hand, the disk capture mechanism proposed by Font-Ribera et al. (2009) does not naturally explain the existence of the brown dwarf desert, as in their model increasingly more massive objects should actually be easier to capture. Also, the observed differences in the mass distribution between isolated objects and companions to solar-type stars, the latter, as shown by Grether & Lineweaver (2006), exhibiting a minimum (the “driest part of the brown dwarf desert”) at $\approx 30 M_J$ ($31^{+25}_{-18} M_J$), do not appear to be readily explainable by this mechanism.

Massive planets and brown dwarfs can also be formed by gravitational fragmentation of extended disks around solar-type primaries. In the models of e.g. Stamatellos & Whitworth (2009), brown dwarfs form by direct gravitational collapse only in the outer regions of the disks, and tend to be scattered further out, or even into the field. This mechanism can explain the existence of the brown dwarf desert at small separations. The two other conclusions that can be drawn from these models are that 1) no planets formed by disk instability can really be found as close companions, as they can only form in the outer regions of the disks and are scattered out with much higher efficiency than brown dwarfs, and b) as a direct consequence short-period Doppler-detected massive planets and brown dwarfs should be preferentially low mass stars. On the one hand, this mechanism can be seen as supported by the data presented here (the properties of massive planets, brown dwarfs and low mass stellar companions being very similar). On the other hand, some of the objects in the sample of Table 3 can hardly be explained by this approach (e.g., the transiting objects XO-3b and CoRoT-3b).

In the still theoretically debated (e.g., Mayer et al. 2002; Rafikov 2005; Stamatellos & Whitworth 2008; Boss 2009; for a review see Durisen et al. 2007) disk instability model of giant planet formation, massive planets with relatively eccentric orbits and moderate to large orbital separations are its more likely product (e.g., Rice et al. 2003; Boley 2009). No clear prediction of the expected shapes of the orbital elements and mass distributions of planets formed by disk instability is yet available, due to the numerical complexities of the simulations and to some still open theoretical issues on the input

⁷ However, see e.g. Boss (2000) and Bate et al. (2002) for alternative scenarios in which isolated planetary mass objects are the result of ejections through dynamical interactions in protoplanetary disks

physics (see e.g. Boss 2009, and references therein). However, if high-precision measurements of the actual masses of massive planets as well as of those of the substellar companions listed in Table 3 were to become available, and they were to prove that these objects are not preferentially low mass stars, this evidence would argue in favor of a common formation mode for massive planets and brown dwarfs.

In the more widely accepted core-accretion mechanism for the formation of giant planets (e.g., Pollack et al. 1996; Alibert et al. 2005; Ida & Lin 2005; for a review see Lissauer & Stevenson 2007) very massive planets and low-mass brown dwarfs on eccentric orbits are not a natural outcome (e.g., Pollack et al. 1996; Alibert et al. 2005; Ida & Lin 2005; Kennedy & Kenyon 2008). However, recent models have shown that this mechanism might also be capable of forming such massive objects. Indeed, in the model of Mordasini et al. (2009) planets with masses as large as $38 M_J$ are formed in long-lived massive disks around a solar mass star. Given the increasingly lower probability of forming very massive planets or brown dwarfs ('deuterium-burning' planets in the words of Baraffe et al. (2008)), the brown dwarf desert appears compatible with the Mordasini et al. (2009) model (for example, the probability of forming objects with masses exceeding the deuterium-burning threshold is found to be $\sim 0.4\%$, in accord with the Marcy & Butler (2000) estimate). While the Mordasini et al. (2009) model does not include multi-planet systems and planet-planet interactions, likely to play an important role in shaping the observed mass, period and eccentricity distributions, we note that the expected location of such very massive planets is between 2 to 5 AU, similar to that observed for HD 38529c, HD 168443c and the object studied in this paper, HD 131664b. However, no prediction of this model on the eccentricity distribution is available, which would be a critical element for discriminating between this mechanism and the other aforementioned options. In addition, super-planets and low-mass brown dwarfs do exist also at small separation, where they are not expected on the basis of the Mordasini et al. (2009) model (e.g., the transiting systems HAT-P-2b (Bakos et al. 2007), WASP-14b (Joshi et al. 2009), XO-3b, and CoRoT-3b, but also other massive objects such as HD 162020b (Udry et al. 2002) and HD 41004Bb (Zucker et al. 2004)).

Finally, of particular interest are the initial claims of a possible correlation between massive planets, eccentric orbits, and large values of the angle between a planetary orbit and the stellar rotation axis, as determined from spectroscopic measurements of the Rossiter-McLaughlin (R-M) effect (Rossiter 1924; McLaughlin 1924) in transiting systems. The XO-3, WASP-14, and HD 80606 systems all have a close-in, massive planet on a very eccentric orbit and with a significant spin-orbit misalignment (e.g., Johnson et al. 2009, and references therein)⁸. At first glance, this might imply that the orbital migration history of massive, eccentric exoplanets is somehow different from that of less massive close-in Jupiters. However, the picture is likely not to be so simple, not only because of the evidence for other transiting systems with massive, eccentric planets (HAT-P-2, HD 17156) showing no signs of spin-orbit misalignment (e.g., Winn et al. 2007; Barbieri et al. 2009), but also for the recent measurements of the R-M effect in transiting

systems with Jupiter-mass planets on circular orbits, such as CoRoT-1, HAT-P-7, and WASP-17 (Pont et al. 2009, and references therein) which point at large values of the projected spin-orbit angles. Overall, the evidence collected so far is a likely indication of the variety of possible outcomes of the complex process of migration to close-in orbits of companions with a wide range of masses, which include a host of proposed dynamical mechanisms (e.g., interactions between a planet and the gaseous/planetesimal disk, planet-planet resonant interactions, close encounters between planets, and secular interactions with a companion star) as well as different formation scenarios. Statistical studies such as the one carried out by Fabrycky & Winn (2009), who showed the emergence of a bimodal distribution of spin-orbit angles, on an increasingly larger sample of transiting systems will ultimately be the optimal way to compare an ensemble of measurements of the R-M effect with the predictions of migration theories.

4.2.2. The impact of binarity

Among the distinctive features of exoplanets discovered around members of various types of binary and triple systems (e.g., Eggenberger & Udry 2009, and references therein), one of the most intriguing is the evidence that solar-type stars members of multiple stellar systems appear to be preferential hosts of the most massive planets in short-period orbits (Desidera & Barbieri 2007), and the fact that the planetary companions with the highest eccentricities all have a stellar or brown dwarf companion (Tamuz et al. 2008). These trends seem to indicate that planet formation and/or migration in binaries may proceed differently than around single stars. Indeed, theoretical studies (Kley 2000; Wu & Murray 2003; Fabrycky & Tremaine 2007) within the context of the core accretion model of giant planet formation suggest that the presence of a fairly close companion significantly enhances the growth rate and make the migration timescale of the planet shorter. On the other hand, the massive super-planets or low-mass brown dwarfs found at separations of about 2-3 AU orbit stars that are single or with very wide companions (HD 38529 has a $0.5 M_\odot$ common proper motion companion at a projected separation of 12000 AU), compatible with long-lived, undisturbed disks required to form such objects according to Mordasini et al. (2009). Models of giant planet formation by disk instability, however, come to opposite conclusions, with giant planet formation significantly suppressed in binaries with separations < 100 AU (Mayer et al. 2005). From inspection of Table 3, the abovementioned trends seem to be supported only in part. For example, the short-period objects HD 98230b and HD 283750b orbit one of the components of wide binaries, but this does not appear to be the case for HD 162020b. Investigations are encouraged which would aim at verifying the possible existence of binary companions to CoRoT-3b and XO-3b. Furthermore, the brown-dwarf candidates with the highest eccentricities do not seem to be preferentially found in multiple systems.

4.2.3. The role of the primary mass and metallicity

In the core-accretion model of giant planet formation, the upper limit on the mass of the planetary companion and the final orbital arrangement are expected to depend on stellar mass and metallicity. Based on arguments of protoplanetary disk size and lifetime as a function of M_\star , one would expect massive planets to be found with higher probabilities around more massive pri-

⁸ While the results are not conclusive due to the presence of systematics in the dataset, it is worth noting that the CoRoT-3 system also exhibits a formally non-zero spin-orbit angle (Triaud et al. 2009). However the large uncertainties reported make the detection of spin-orbit misalignment in the CoRoT-3 system only marginal.

maries (Kennedy & Kenyon 2008), and at typically moderate to large separations (Burkert & Ida 2007; Currie 2009). Indeed, the observational evidence indicates that, for larger stellar masses, massive companions with $\geq 10 M_J$ are significantly more numerous than around solar type stars (e.g., Lovis & Mayor 2007; Johnson 2008. For a review see Hatzes (2008), and references therein). On the opposite end, M dwarfs are expected to show a paucity of giant planets (Laughlin et al. 2004; Ida & Lin 2005), which is also observed (Endl et al. 2006; Johnson et al. 2007; Bailey et al. 2009). The core accretion mechanism also naturally predicts that super-massive planets should not be found at all around metal-poor stars, given the lack of material for accumulation (e.g., Ida & Lin 2005). The alternative disk instability mechanism is instead rather insensitive to the values of M_\star and $[\text{Fe}/\text{H}]$ of the stellar host (e.g., Boss 2002, 2006). As a consequence, a qualitative prediction of this model (e.g., Rice et al. 2003) is that massive planets found on moderate to large separations around massive and/or metal-deficient hosts would be likely to have been formed by gravitational instability. In this respect, the data collected here and the results of the statistical analysis, that corroborate the findings of Ribas & Miralda-Escudé (2007), can be read as partly supportive of the latter view. Interestingly, the frequency of (massive) planets (f_p) around intermediate-mass (mostly giant) stars appears to be rather independent of $[\text{Fe}/\text{H}]$ (Hatzes 2008). However, the four known planet - brown dwarf systems (HD 38529, HD 168443, HD 202206, HAT-P-13) all have super-solar mass, very metal-rich (main-sequence) primaries. The latter evidence might be seen as supportive of the core accretion formation mode, while the former dataset might point to a significant role of the disk instability mechanism. However, the global picture is likely to rather complex. For example, Doppler surveys for giant planets around intermediate-mass stars typically include targets which are evolved to some degree, given that massive main sequence stars are unsuitable for high-precision radial-velocity measurements (too few spectral lines, often broadened by high rotation rates). The very different dependence of f_p on $[\text{Fe}/\text{H}]$ for intermediate-mass stars with respect to their solar-mass counter-parts might then reflect a non-primordial origin of the metallicity enhancement in solar-type planet hosts (Pasquini et al. 2007) rather than point to different formation modes.

As for the possible dependence of brown dwarf frequency on stellar mass and metallicity, this is still a poorly understood issue. A quick look at literature data allows to speculate on the possibility that the brown dwarf desert may not be so ‘dry’ when it comes to close sub-stellar companions to intermediate-mass stars, in light of a handful of systems containing at least one companion with minimum mass in the brown dwarf regime (e.g., Omiya et al. 2009, and references therein). In particular, the recently announced system of brown dwarfs around BD+20 2457 (Niedzielski et al. 2009) has an architecture very similar to that of HD 168443, with a solar-type primary. It is reminiscent of an origin in a massive circumstellar disk, further suggesting a scenario in which more massive sub-stellar companions are found around more massive stellar hosts (and their frequency also increases with increasing primary mass). Such systems would be more likely to have formed by local gravitational instabilities in protoplanetary disks (e.g., Rice et al. 2003) rather than protostellar cloud fragmentation, given the difficulties in forming extreme mass-ratio binaries by the latter mechanism (e.g., Bate 2000). However, the combination of small-number statistics, the different priority given to observations of stars with very massive companions in Doppler surveys, the variable detection thresholds as a function of companion mass and separation

due to the decreasing radial-velocity precision in increasingly higher mass stars, and the uncertainty on the actual mass values for most of the objects included in Table 3 (as well as those referenced above) prevents one, as of today, from drawing any serious conclusions on the possibility that the brown dwarf desert may move in mass and/or separation range depending on M_\star and $[\text{Fe}/\text{H}]$.

4.2.4. Structural and atmospheric models

Finally, one of the most effective ways of distinguishing between massive planets and brown dwarfs is through a comparison of their internal structure properties and of the composition of their atmospheres (e.g., Chabrier et al. 2009; Burgasser 2009). Studies at this level are still in their infancy status, particularly for what concerns the possibility of determining the actual nature of such objects based on their condensate cloud formation properties, non-equilibrium chemistry, and atmospheric dynamics (Burgasser 2009). However, the class of transiting systems is already providing data of relevance. For example, Mordasini et al. (2009) have proposed that massive planets might have a large content of heavy elements (about $0.8 M_J$ for the individual case shown in their Fig. 12). In the case of the transiting massive planet HD 147506b (HAT-P-2b), with a mass of $9.04 M_J$ and $R = 0.982 R_J$ (Bakos et al. 2007), just below the threshold of $10 M_J$ adopted here for inclusion in Table 3, Baraffe et al. (2008) and Leconte et al. (2009) argue from the measured radius for a total amount of heavy elements of about $1 M_J$, excluding a gaseous H/He object with solar composition. This indicates that indeed $10 M_J$ planets might be formed by the core accretion mechanism, unless such a large mass is the result of planetary collision, as speculated by Baraffe et al. (2008). In the case of the super-massive transiting planet XO-3b, despite its rather uncertain radius (due to discrepancies in the stellar radius estimates from photometry and spectroscopy), there seems to be no need for a large content of heavy elements in the core (Winn et al. 2008). Similarly, the $22 M_J$ transiting object CoRoT-3b fits the Baraffe et al. (2008) models for solar composition, without need for large metal enrichment (Leconte et al. 2009). Both HAT-P-2b and CoRoT-3b have surface gravities similar to those of young, very low-mass brown dwarfs such as AB Pic (see Figure 2 of Burgasser 2009), suggesting an overlap in the parameter space of some physical properties (e.g., gas pressure, temperature). Interestingly, as discussed by Deleuil et al. (2008), all transiting massive planets orbit stars more massive than the Sun, as predicted by the core accretion model of planet formation. On the other hand, their actual existence on such short periods and relatively eccentric orbits (except for CoRoT-3b), and the fact that the metallicities of their parent stars are not skewed towards super-solar values calls for the possibility of differences in their origin.

In conclusion, the present-day evidence on the orbital and structural properties of massive planets and brown dwarfs as close companions to nearby solar-type stars can be interpreted as supportive of a picture in which different mechanisms for the formation of such objects are at work. The above discussion also indicates how the lack of a clean, statistically significant sample of high-mass planets and brown dwarf companions to solar-type stars with well-determined mass estimates hampers the possibility to conclusively discriminate among the various competing modes of formation of such objects. From an observational viewpoint, improvements in the determination of the multiplicity properties of sub-stellar companions are very much needed, and they will be obtained in the near future through

the combined contribution of a variety of techniques. For example, some of the massive planets and brown dwarfs objects in Table 3 are within reach of next generation direct imaging instruments such as SPHERE (Beuzit et al. 2008) and for many of them true masses will be measured with high precision by ground-based and space-borne astrometric observatories, such as VLTI/PRIMA and Gaia (e.g., Launhardt et al. 2008; Casertano et al. 2008; Sozzetti 2009, and references therein). The possibility that objects with similar masses formed in different way and exhibit different chemical composition depending on the formation mechanism open exciting perspectives for such instruments. Therefore, they will represent key benchmarks for the calibration of the masses of substellar objects, for furthering our understanding of the dependence of the brown dwarf desert on the properties of the stellar hosts, and even for reaching final agreement on the actual definition of planets and brown dwarfs themselves based not simply on semantics but rather on robust physical grounds.

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Table 3. Close companions to solar-type stars with (projected) masses between $10 M_J$ and $80 M_J$. The first part lists the probable true substellar objects, the second part the objects for which only the projected masses or poor constraints on the true mass are available, the third part the companions with true masses above the substellar limit. In the remarks, PL refers to objects with additional companions of planetary mass, MULT multiple systems (additional stellar companions), HIPG stars with Hipparcos acceleration solutions.

Object	$M_c \sin i$ M_J	Period d	a AU	e	i deg	M_c M_J	SpT	Mstar M_\odot	[Fe/H]	Remarks and References
Probable substellar objects with mass $M_c > 10 M_J$ and $a < 7$ AU around solar-type stars										
HD29587b	41	1474.9		0.356		41 (27)	G2V	1.00	-0.61	Halbwachs et al. (2000), Bensby et al. (2005) ^a
HD38529c	12.7	2174.3	3.68	0.36	160	37^{+36}_{-19}	G4IV	1.46	+0.45	Butler et al. (2006), Reffert & Quirrenbach (2006), Valenti & Fischer (2005), PL, MULT, HIPG
HD89707b	59	297.708		0.952		64 (19)	G1V	1.05	-0.42	Halbwachs et al. (2000), Edvardsson et al. (1993) ^b
HD127506b	36	2599		0.716		45 (21)	K3V	0.75	+0.06	Halbwachs et al. (2000), Han et al. (2001)
HD131664b	18.15	1951	3.17	0.638	55 ± 12	23^{+26}_{-5}	G3V	1.10	+0.32	this paper, HIPG
HD168443c	18.1	1765.8	2.91	0.2125	150	34 ± 12	G5	1.08	+0.08	Reffert & Quirrenbach (2006), PL
CoRoT-3b		4.2568	0.057	0.0	85.9	21.7 ± 1.0	F3V	1.37	-0.02	Zucker & Mazeh (2001)
XO-3b		3.19152	0.0454	0.26	84.20	11.79 ± 0.59	F5V	1.21	-0.18	Deleuil et al. (2008), transit ^c Winn et al. (2008), transit ^d
Objects with projected mass $10 < M_c \sin i < 80 M_J$ and $a < 7$ AU around solar-type stars										
HD4747b	42.3	6832.0	6.70	0.64				0.82	-0.22	Nidever et al. (2002), Valenti & Fischer (2005)
HD13507b	52	3000	4.3	0.14			G0	1.00	+0.03	Perrier et al. (2003), Valenti & Fischer (2005) ^e
HD16760b	13.13	466.47	1.084	0.084			G5V	0.78	+0.07	Sato et al. (2009), Bouchy et al. (2009), MULT
HD30339b	77.8	15.0778	0.13	0.25			F8	1.39	+0.26	Nidever et al. (2002), Valenti & Fischer (2005)
HD39091b	10.35	2063.818	3.29	0.62			G1IV	1.10	+0.05	Butler et al. (2006), Valenti & Fischer (2005)
HD65430b	67.8	3138.0	4.00	0.32				0.83	-0.12	Nidever et al. (2002), Valenti & Fischer (2005)
HD91669b	30.6	497.5	1.205	0.448				0.91	+0.31	Wittenmyer et al. (2009),
HD98230b	35	3.9805		0.0				0.86	-0.35	Fuhrmann (2008), MULT ^f
HD114762b	11.02	83.90	0.3	0.34			F9V	0.93	-0.65	Halbwachs et al. (2000), MULT ^g
HD136118b	11.9	1209	2.3	0.37			F9V	1.25	-0.05	Butler et al. (2006), Valenti & Fischer (2005)
HD137510	26	798.2	1.85	0.402	> 16	< 94	G0IV	1.41	+0.37	Endl et al. (2004), Valenti & Fischer (2005)
HD156846b	10.45	359.51	0.99	0.8472			G0V	1.43	+0.22	Tamuz et al. (2008), MULT
HD162020b	13.75	8.428198	0.072	0.277			K2V	0.78	+0.11	Udry et al. (2002) ^h
HD167665b	50.3	4385	5.47	0.337			G0V	1.11	-0.17	Patel et al. (2007), Valenti & Fischer (2005)
HD174457b	65.8	840.800	1.90	0.23				1.07	-0.18	Nidever et al. (2002), Valenti & Fischer (2005)
HD184860b	32.0	693	1.4	0.67			K2V	0.77	-0.04	Vogt et al. (2002), Valenti & Fischer (2005), MULT
HD191760b	38.17	505.65	1.35	0.63			G3IV/V	1.28	+0.29	Jenkins et al. (2009)
HD202206b	17.4	255.87	0.83	0.435		< 149	G6V	1.17	+0.35	Correia et al. (2005), Zucker & Mazeh (2001), PL
HD283750b	51	1.788		0.002			dK5	0.67	+0.03	Halbwachs et al. (2000), MULT ⁱ
TYC 2534-698-1b	39.7	103.698	0.44	0.385			G2V	1.00	-0.25	Kane et al. (2009)
HAT-P-13c	15.2	428.5	1.19	0.691			G4V	1.22	+0.43	Bakos et al. (2009), PL
Probable stellar companions with projected mass in the substellar range										
HD18445B	45	554.6		0.558		187 (20)	K2V	0.78	0.00	Halbwachs et al. (2000), Valenti & Fischer (2005), MULT ^j Zucker & Mazeh (2001)
HD33636B	9.3	2128		0.48	-16.1	178 ± 20		1.02	-0.13	Bean et al. (2007)
HD43848B	25	2371	3.4	0.69	4.1 ± 0.1	$142^{+3.3}_{-1.6}$	G0V	0.89	-0.03	this paper, HIPG
HD110833B	17	271.17		0.784	55 ± 12	$120^{+1.6}_{-0.7}$	K3V	0.72	0.00	Halbwachs et al. (2000), Mishenina et al. (2004) ^k Zucker & Mazeh (2001)
HD112758B	34	103.258		0.139	7.76	143 ± 12	K0V	0.79	-0.56	Halbwachs et al. (2000), Mishenina et al. (2004)
HD140913B	43.2	147.968	0.55	0.54	10.4	$212 (44)$ 213 ± 43		1.17	+0.13	Zucker & Mazeh (2001)
HD164427B	46	108.55	0.46	0.55	16.3	$177 (73)$ 181 ± 74		1.18	+0.13	Nidever et al. (2002), Halbwachs et al. (2000)
HD169822B	27.2	293.1	0.84	0.48	8.5	372^{+106}_{-85} < 190	G5V	0.91	-0.12	Zucker & Mazeh (2001), Valenti & Fischer (2005) ^l Zucker & Mazeh (2001)
HD217580B	68	454.66		0.520	175	320	K4V	0.69	-0.06	Tinney et al. (2001)
BD-04 782B	48	716.68		0.074	25.2	$171 (14)$ 172 ± 15 $261 (15)$ 257 ± 16	G5V K5V	0.91 0.67	-0.12 +0.05	Vogt et al. (2002), MULT ^m Halbwachs et al. (2000), Gray et al. (2003) ⁿ Zucker & Mazeh (2001) Halbwachs et al. (2000), Heiter & Luck (2003) ^o Zucker & Mazeh (2001)

^a For spectroscopic binaries with brown dwarf candidates observed by Hipparcos and with an actual mass estimate derived by Halbwachs et al. (2000), the error distribution of the secondary masses is not Gaussian and not symmetric. We have listed here the values of M_c and the accompanying one-sided errors as defined by Eq. 5 in Halbwachs et al. (2000). The star has both chemical abundances and kinematics of thick disk.

^b Thick disk population.

^c Transiting system. Triaud et al. (2009) found a significant misalignment between the planetary orbital axis and the stellar rotation axis ($37.6^{+10.0}_{-22.3}$ deg).

^d Transiting system. Winn et al. (2009) found a significant misalignment between the planetary orbital axis and the stellar rotation axis (37.3 ± 3.7 deg).

^e The orbit in Perrier et al. (2003) is preliminary, with only limited phase coverage. Perrier et al. (2003) also reported no detection with AO.

^f Assuming synchronous rotation and orbit alignment Fuhrmann (2008) derived $i = 15$ and $M_c = 0.14^{+0.09}_{-0.05} M_\odot$ for the companion. The system is a quadruple with another SB at $a = 2.53$ arcsec (21 AU) with $e=0.41$ from HD98230.

^g The possibility that the star is seen nearly pole-on because of its very small projected rotational velocity is widely debated in the literature. Halbwachs et al. (2000) derived a very uncertain astrometric mass $112 M_J$ with an error of $103 M_J$. Additional low-mass companion close to the substellar boundary detected at 130 AU by Patience et al. (2002). Member of the thick disk population.

^h Zucker & Mazeh (2001) derived an astrometric solution that gives a companion mass of $3.0 \pm 0.94 M_\odot$. Not compatible with the stellar properties of the primary. Probably spurious due to the short orbital period.

ⁱ Halbwachs et al. (2000) derived an astrometric mass of $182 M_J$ with a large error of $470 M_J$. Glebocki & Stawikowski (1995) estimate $i = 22 \pm 10$ and then $M = 136 \pm 39 M_J$ from the rotation period (synchronous with the orbit) and projected rotational velocity, assuming the rotation axis is perpendicular to the orbital plane. However, misalignments can not be ruled out, especially considering that the system has a wide WD companion. The system is probably associated with the Hyades (Catalan et al. 2008). Metallicity from Catalan et al. (2008).

^j Also resolved with direct imaging by Beuzit et al. (2004). Quintuple system (see Bonavita & Desidera (2007) and references therein).

^k Purely astrometric orbital solution in Hipparcos.